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Medium-Sulfur Coal and Fly Ash Resistivity

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16. ABSTRACT The paper describes a project to expand the data base of SO_3/SO_2 concentrations, in situ fly ash resistivities, and electrical operating points measured in operating utility fly ash electrostatic precipitators (ESPs). Recent data are presented. In situ resistivity data are compared with laboratory measurements and mathematical predictions. (NOTE: Electric generating plants burning medium-sulfur coal need a way to predict when ESP performance will be limited by high resistivity of the collected fly ash. The main uncertainty in mathematical predictions of fly ash resistivity lies in the marginal effect of SO_3 vapor naturally occurring in the flue gas.)

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Coal		21D
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Medium-Sulfur Coal and Fly Ash Resistivity

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Electric generating plants burning medium-sulfur coal need a way to predict when ESP performance will be limited by high electrical resistivity of the collected fly ash. The main uncertainty in mathematical predictions of fly ash resistivity lies in the marginal effect of naturally occurring SO_3 vapor in the flue gas. This paper results from a project to expand the data base of SO_3/SO_2 concentrations and fly ash resistivities measured in utility fly ash precipitators. Complete data sets are presented from three plants in the Southern Company electric system. In situ resistivity data are compared with laboratory measurements and with two different mathematical predictions of resistivity based on coal and ash analyses. The revised version of the resistivity predictor gives results in good agreement with resistivity values measured both in situ and in the laboratory.

This paper describes a joint endeavor between the U.S. Environmental Protection Agency (EPA), Southern Research Institute (SRI), and Southern Company Services (SCS) to expand the existing data on the relationship between coal sulfur and the amount of sulfur trioxide (SO_3) available in the flue gas for fly ash resistivity modification. The reasons for selecting medium-sulfur coal for this program are related to the impact of fly ash resistivity on the electrical operating condition of an electrostatic precipitator (ESP). Medium-sulfur coal is defined as coal having between 1 and 2 percent sulfur. The combustion of low-sulfur coals (<1 percent sulfur) with highly alkaline ash will produce a very small amount of SO_3 in the flue gas entering the ESP. The collected fly ash will have high electrical resistivity which severely limits the useful electrical power input to a cold-side ESP. The combustion of high-sulfur coal (>2 percent sulfur) will produce sufficient SO_3 to condition the fly ash. The conditioning results in low-resistivity fly ash which presents few electrical operating problems to a cold-side ESP. In the intermediate case, however, the existing data for medium-sulfur coal exhibit considerable scatter in the relationship between the SO_2 and SO_3 in the flue gas entering the ESP. The scatter in the data makes the prediction of SO_3 values extremely difficult. It is advantageous to be able to predict what levels of SO_3 will be available from a particular coal and what effect the SO_3 will have on fly ash resistivity; as one can then predict what impact the coal will have on the electrical operation of an ESP.

SCS is the engineering and design company for The Southern Company, one of the nation's largest public utility holding companies, with some 232 generating units providing over 24,000 MW of electrical power. About 80 percent of these units are coal-fired and use precipitators for particulate control. SCS engages in research and development programs concerning ESP technology to assist its operating companies: Alabama Power, Georgia Power, Gulf Power, and Mississippi Power. EPA sponsored the development of fly ash resistivity predictors over several years of laboratory research at SRI and sponsored the comparative tests of resistivity data presented in this paper. The point-plane resistivity probe and the two Bickelhaupt computer models are techniques developed at SRI and used for collecting and analyzing the data presented in this paper.

Test Program

Complete data sets from three plants in the Southern Company electric system are presented. Measurements and sample collections were performed over a three-day period at each plant. The data include fly ash resistivity measured in situ with two different probes, flue gas composition including SO_2 and SO_3, coal analyses, and fly ash analyses. In situ resistivity data, flue gas analyses, ash samples, and coal samples were obtained simultaneously. Variations in coal and boiler firing conditions make it essential that all data needed to compare fly ash resistivity values be obtained simultaneously. Three methods were used to determine fly ash resistivity values:

1. Bickelhaupt resistivity predictors, Models I and II;
2. laboratory resistivity measurements, IEEE Standard 548-1984 using descending temperature, and a modified standard with SO_3; and
3. in situ resistivity measurements, using a point-plane probe and the spark method.

The objective of this presentation of the test results is to compare the three methods of determining fly ash resistivity values, with the same coal and boiler operation.

Measurements

A description of the laboratory measurements of fly ash resistivity, with and without the effect of sulfuric acid vapor,

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Table I. Plant 1 coal, ash, and gas analyses.

	7/30/85 PM		7/31/85 PM	8/1/85 AM	
Coal analysis					
C wt%	73.29		74.16	72.72	
H_2	4.36		4.34	4.39	
O_2	5.55		4.55	5.11	
N_2	1.54		1.58	1.53	
S	0.84		0.78	0.81	
H_2O	1.69		1.71	1.96	
Ash	12.60		12.00	12.50	
Computed gas composition					
H_2O %	6.9		6.8	7.0	
SO_2 ppm	570.0		530.0	560.0	
SO_3 ppm (Model I)	2.4		2.3	2.4	
SO_3 ppm (Model II)	2.2		2.1	2.2	
Measured gas composition					
H_2O wt%	9.3		9.3	9.4	
SO_2 ppm	626.0		543.0	594.0	
SO_3 ppm	3.6		2.0	1.6	
Measured gas temperature					
Gas sampling port, °F	380		375	350	
Resistivity ports, °F	340		335	300	
Ash analysis	SCS in situ	SRI in situ	SCS in situ	SCS in situ	SRI in situ
Na_2O wt%	0.41	0.49	0.44	0.11	0.43
K_2O	2.58	2.84	2.63	2.55	2.84
MgO	0.00	1.19	1.17	1.25	1.23
CaO	1.39	1.42	2.23	2.18	1.85
Fe_2O_3	8.62	6.15	7.43	8.88	6.35
Al_2O_3	28.00	27.60	28.20	27.15	26.40
SiO_2	53.79	54.70	55.23	53.40	53.70
TiO_2	1.33	1.36	1.36	1.31	1.27
P_2O_5	0.47	0.29	0.57	0.47	0.27
SO_3	0.43	0.13	0.22	0.47	0.15
LOI	—	3.34	—	—	5.11

is given in Reference 1. The volume resistivity measurement at high temperature is calibrated with an NBS standard sample of lead-silica glass. The accuracy of the measurement over the entire temperature range is estimated to be one-half order of magnitude. The precision (reproducibility) of the measurement is determined to be ±30 percent.

Significant changes in fly ash resistivity (changes which significantly impact the electrical operation of an ESP) occur over orders of magnitude. Therefore, agreement within a half-order of magnitude between different determinations of fly ash resistivity values is considered to be good agreement.

A description of the in situ measurements of both fly ash resistivity and sulfuric acid vapor concentration is given in Reference 2. Based on comparisons with laboratory resistivity measurements over the past 10 years (including the data presented in this paper) the accuracy of in situ resistivity measurements performed with the point-plane probe is estimated to be one-half order of magnitude. The precision of the in situ resistivity data is estimated to be within a factor of two. Both the accuracy and precision of the measurement of SO_3 concentration by the Cheney-Homolya method of controlled condensations are estimated to be ±10 percent.

Models

Two versions of the Bickelhaupt resistivity predictor, Models I and II, are available from the National Technical Information Service.[3,4] Both computer models produce tabulated output data for resistivity versus temperature. One column of data gives the resistivity predicted without SO_3 conditioning. Another column gives the resistivity predicted with conditioning by the predicted amount of SO_3. In addition, Model II produces tabulated data for the effect of 1, 4, and 10 ppm SO_3 on the fly ash resistivity. Model II calculates the dewpoint temperature for the H_2O concentration and each of the four SO_3 concentrations and terminates the table of ash resistivity predictions at that point.

Both computer models predict the concentrations of H_2O and SO_2 from a stoichiometric combustion calculation assuming 30 percent excess air. (The excess air value can be changed in the computer code if desired by the user.) An empirical SO_3/SO_2 ratio is used to predict the residual SO_3 concentration in the flue gas entering the ESP. In Model I, this ratio is always 0.004. Model II takes into account the percentage of ash and the mineral analysis of the ash in predicting the SO_3 concentration. Therefore, different SO_3 concentrations can be predicted by Models I and II. In the absence of SO_3, the only difference in the resistivity predictions is a correction in Model II for the increased sensitivity to moisture of highly alkaline fly ashes.

The most significant difference between the models is that Model II uses a completely different mathematical algorithm for computing the effect of SO_3 on fly ash resistivity. The new algorithm is tied more closely to the mineral composition of the fly ash. For the ashes encountered in this test program, Model II tends to shift the peak of the resistivity-temperature curve to higher temperature and lower resistivity. This test program is the first systematic comparison of laboratory resistivity measurements, in situ resistivity measurements, and resistivity predictions of both Models I and II.

Table II. Plant 2 coal, ash, and gas analyses.

	8/20/85 PM		8/21/85 PM		8/22/85 AM		8/22/85 PM	
Coal analysis								
C wt%	69.28		71.24		68.99		69.58	
H_2	4.55		4.77		4.55		4.66	
O_2	5.73		6.44		5.35		6.03	
N_2	1.66		1.70		1.66		1.69	
S	1.69		1.38		1.36		1.29	
H_2O	3.58		4.08		5.41		5.24	
Ash	13.49		10.32		12.66		11.49	
Computed gas composition								
H_2O %	7.5		7.7		7.7		7.8	
SO_2 ppm	1200.0		939.0		950.0		900.0	
SO_3 ppm (Model I)	5.2		4.1		4.1		3.9	
SO_3 ppm (Model II)	4.6		3.7		3.7		3.5	
Measured gas composition								
H_2O %	9.8		9.2		8.9		8.9	
SO_2 ppm	1051.0		995.0		965.0		924.0	
SO_3 ppm	0.50		0.82		0.42		0.37	
Measured gas temperature								
Gas sampling port, °F	290		290		285		285	
Resistivity ports, °F	290		285		280		285	
Ash analysis	in situ	hopper	in situ	hopper	in situ	hopper	in situ	hopper
Na_2O wt%	0.43	0.43	0.39	0.41	0.43	0.41	0.45	0.41
K_2O	3.66	3.38	3.30	3.30	3.60	3.24	3.65	3.31
MgO	1.27	1.21	1.14	1.16	1.29	1.14	1.31	1.17
CaO	1.02	0.98	1.18	1.10	1.02	1.12	1.07	1.02
Fe_2O_3	8.45	8.43	10.13	8.66	9.05	8.44	8.42	8.27
Al_2O_3	26.30	24.00	26.00	24.30	26.40	23.80	26.90	24.60
SiO_2	52.90	45.40	51.70	45.40	52.60	43.40	52.50	45.70
TiO_2	1.17	1.06	1.25	1.12	1.12	1.03	1.18	1.07
P_2O_5	0.38	0.44	0.48	0.42	0.43	0.44	0.37	0.39
SO_3	0.30	0.95	0.27	1.05	0.20	1.00	0.53	0.70
LOI	3.87	13.49	3.97	12.84	3.70	15.75	3.43	13.12

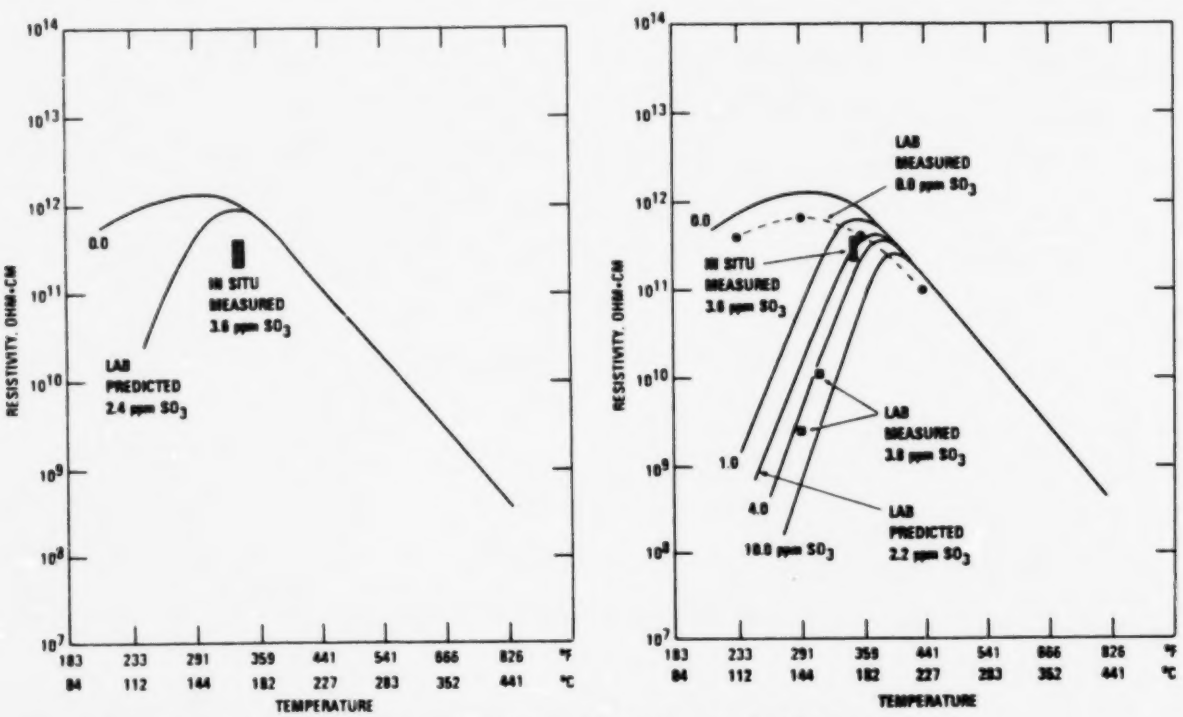

Figure 1. Plant 1 fly ash resistivity data, 7/30/85 PM, with Model I (left) and Model II (right) predicted resistivity curves.

Table III. Plant 3 coal, ash, and gas analyses.

	8/28/85 AM		8/28/85 PM	8/29/85 AM		8/29/85 PM
Coal analysis						
C wt%	69.50		71.44	68.41		68.80
H_2	4.26		4.44	4.05		4.16
O_2	5.41		5.31	4.65		4.60
N_2	1.52		1.58	1.44		1.47
S	2.15		2.18	1.65		1.73
H_2O	4.99		2.72	5.90		5.72
Ash	12.07		12.22	13.83		13.44
Computed gas composition						
H_2O %	7.4		7.2	7.4		7.4
SO_2 ppm	1520.0		1500.0	1200.0		1240.0
SO_3 ppm (Model I)	6.6		6.4	5.2		5.3
SO_3 ppm (Model II)	5.9		5.9	4.6		4.8
Measured gas composition						
H_2O %	8.5		8.5	8.6		8.6
SO_2 ppm	1580.0		1386.7	1178.8		1190.0
SO_3 ppm	7.6		6.8	7.7		7.9
Measured gas temperature						
Gas sampling port, °F	360–370		370	360		370
Resistivity ports, °F	340–350		340–360	335–345		345–355
Ash analysis	SRI in situ	SCS in situ	SRI in situ	SRI in situ	SCS in situ	SRI in situ
Na_2O wt%	0.25	0.26	0.26	0.23	0.24	0.22
K_2O	2.91	2.87	2.94	2.85	2.94	3.09
MgO	1.02	1.01	1.04	1.04	1.08	1.09
CaO	0.76	0.86	0.80	0.60	0.67	0.66
Fe_2O_3	17.04	15.64	11.43	11.58	11.69	9.80
Al_2O_3	23.10	23.10	24.60	24.60	25.10	24.80
SiO_2	45.30	47.10	48.30	48.50	49.80	51.00
TiO_2	0.93	0.96	1.06	1.00	1.01	0.98
P_2O_5	0.28	0.33	0.32	0.32	0.31	0.49
SO_3	0.45	0.40	0.38	0.38	0.30	0.35
LOI	7.65	7.04	8.48	8.56	6.44	7.31

The resistivity models are based on laboratory resistivity measurements performed on a large number of fly ashes having large variations in their mineral composition.[3,4] Laboratory resistivity measurements with SO_3 are performed on thin (1 mm) ash samples maintained at a constant temperature and under a continuous, steady flow of H_2O and SO_3 vapors until the measured resistivity stabilizes at its lowest value.[3] It follows that model predictions of fly ash resistivity in a precipitator involve the implicit assumption that the fly ash is fully conditioned by the SO_3 value that is used in the model. The SO_3 value is assumed to be a residual vapor concentration that is uniformly distributed in the flue gas and is in equilibrium with the fly ash.

Results

Complete data sets from the coal, ash, and gas analyses are presented in Tables I, II, and III for the three electric generating plants. These tables include all data that form complete sets and were collected simultaneously. Water vapor in the flue gas is given in volume percent, and SO_2 and SO_3 are given in volume ppm. The ultimate coal analyses (in weight percent) and the ash mineral analyses (in weight percent as the oxide) constitute complete input data for the resistivity models. Two representative comparisons of measured and computed resistivities for each plant are shown in Figures 1 through 6.

There are several ambiguities in the day-to-day variations in the data presented in the tables. The test program did not permit a detailed resolution of site-specific ambiguities which are typically encountered in field tests. Rather, the data were treated with a view toward the objective of determining what combinations of measurements and predictions (ordinary ambiguities included) can yield dependable values of fly ash resistivity.

Two of the three complete data sets collected at Plant I (Table I) are illustrated in Figures 1 and 2. (Individual data sets are indentified by date and time.) For both data sets, Model I predicts an SO_3 concentration of 2.4 ppm and Model II predicts 2.2 ppm. The SO_3 concentration measured in situ changed substantially, from 3.6 ppm on the first test day to 1.6 ppm on the third test day, and this change is unexplained. Each reported SO_3 value is an average of several measurements. In both data sets, the Model II resistivity curves agree better with the in situ measurements than do the Model I curves. Figure 2 shows that identical values of resistivity were measured in situ on the third test day by two different point-plane probes operated independently in two different ports by SRI and SCS personnel. (Whenever there were independent and simultaneous resistivity measurements in situ, two distinct data points are shown on the figures.)

Figure 1 shows that the gas temperature on the first test day was high, about 340°F. Because of the high gas temperature and low SO_3 concentration, SO_3 was expected to have little effect on the fly ash resistivity. In fact, the difference in the predictions of Model I and II is particularly apparent at this high temperature. Model I predicts that the SO_3 will have no effect on the fly ash resistivity. However, Model II shifts the peak of the resistivity curve to higher temperature and lower resistivity. Because the measured SO_3 was expected to have little effect on fly ash resistivity, the subsequent laboratory resistivity measurements were performed at lower temperatures and with higher SO_3 concentrations. (A

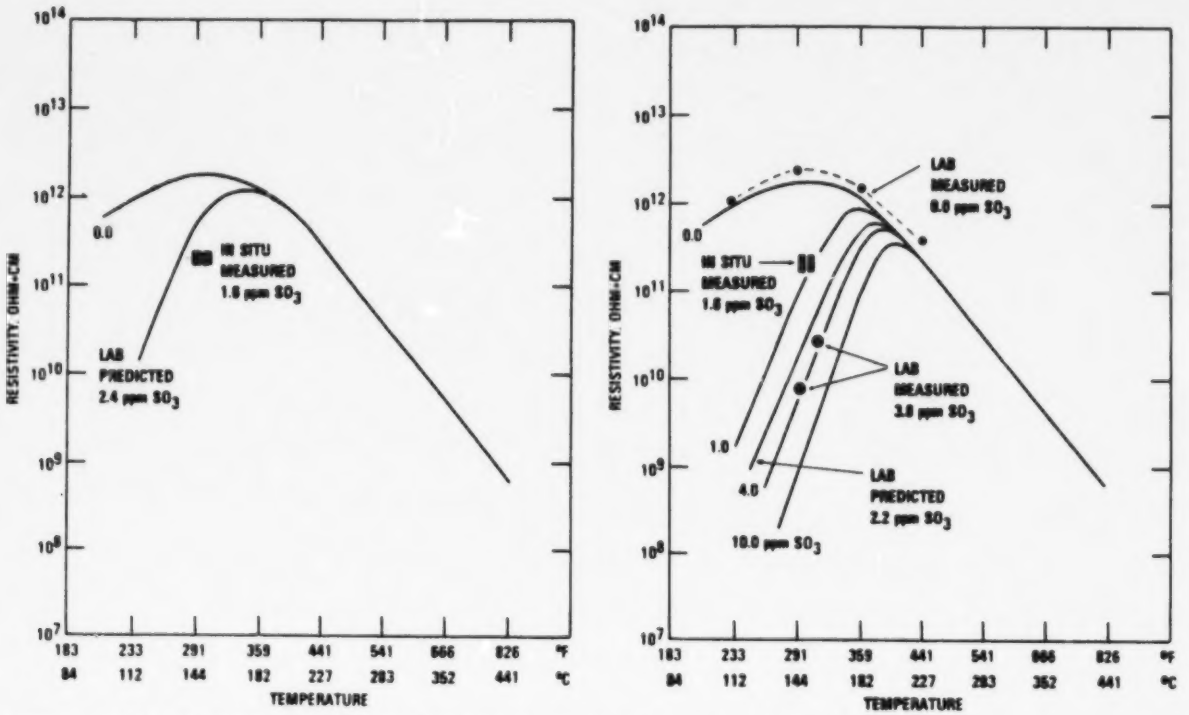
RESISTIVITY, OHM-CM
TEMPERATURE
IN SITU MEASURED 1.8 ppm SO_3
LAB PREDICTED 2.4 ppm SO_3
LAB MEASURED 0.0 ppm SO_3
LAB MEASURED 3.8 ppm SO_3
LAB PREDICTED 2.2 ppm SO_3
10.0 ppm SO_3

Figure 2. Plant 1 fly ash resistivity data, 8/1/85 AM, with Model I (left) and Model II (right) predicted resistivity curves.

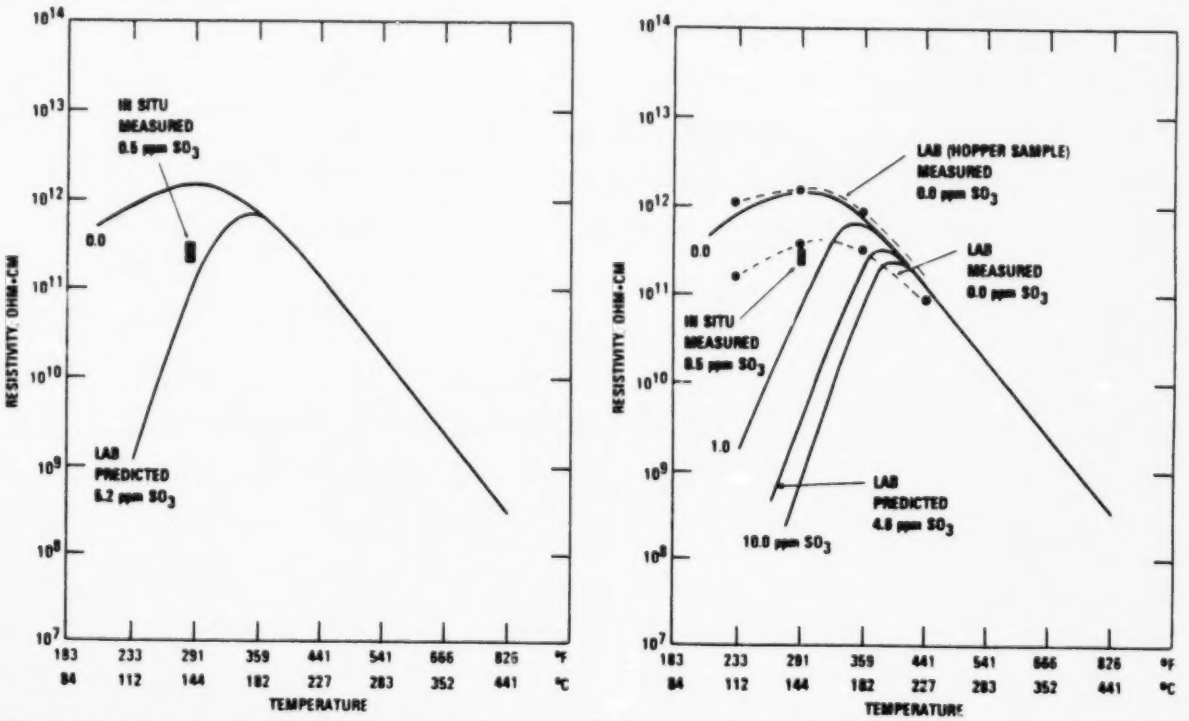
RESISTIVITY, OHM-CM
TEMPERATURE
IN SITU MEASURED 8.5 ppm SO_3
LAB PREDICTED 8.2 ppm SO_3
LAB (HOPPER SAMPLE) MEASURED 0.0 ppm SO_3
LAB MEASURED 0.0 ppm SO_3
LAB PREDICTED 4.8 ppm SO_3
10.0 ppm SO_3

Figure 3. Plant 2 fly ash resistivity data, 8/20/85 PM, with Model I (left) and Model II (right) predicted resistivity curves.

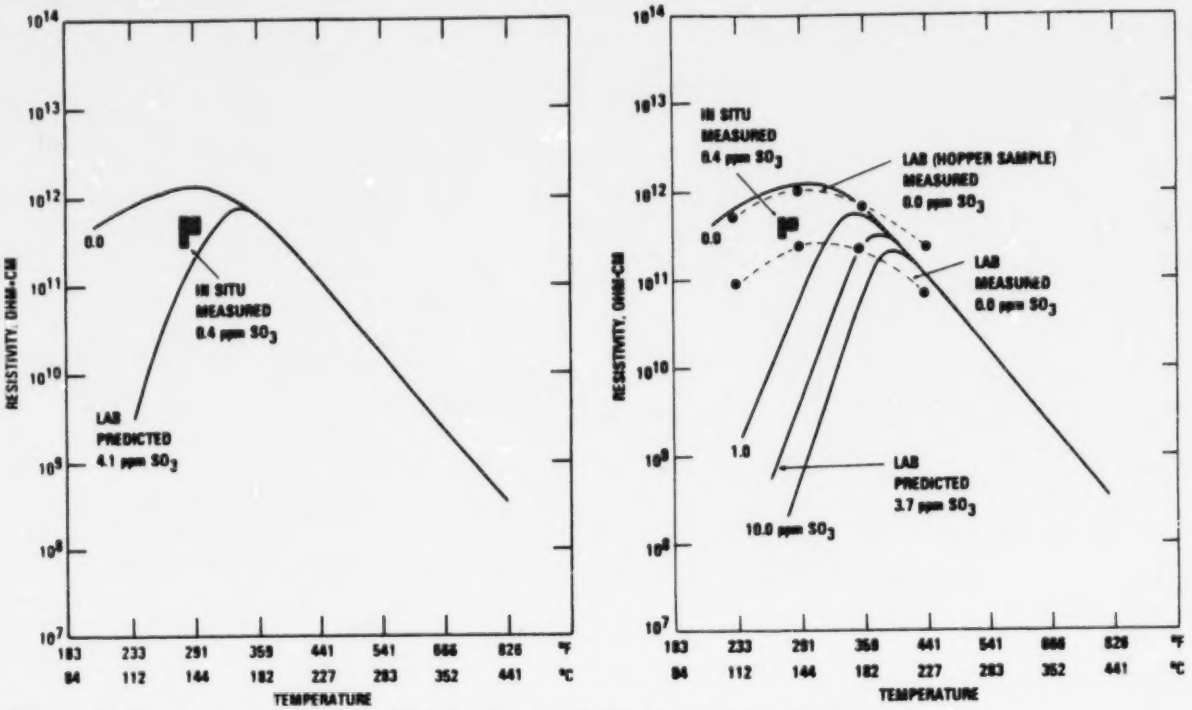

Figure 4. Plant 2 fly ash resistivity data, 8/22/85 AM, with Model I (left) and Model II (right) predicted resistivity curves.

similar procedure was followed with data from Plant 3, discussed below.) Thus, the laboratory resistivity measurements with SO_3 do not compare directly with the in situ resistivity data. Instead, both types of measured resistivity data are superimposed on the predicted resistivity curves.

Laboratory resistivity measurements were performed by SRI on fly ash precipitated inside the casing of the SRI point-plane resistivity probe. The measurements were performed without SO_3, as a function of temperature, and with 3.8 ppm SO_3 at two different temperatures. Figures 1 and 2 show that the laboratory measurements agree well with the resistivity curves predicted by Model II.

Two of the four complete data sets collected at Plant 2 (Table II) are illustrated in Figures 3 and 4. These data give a comparison of predicted and measured resistivity values when the computer models predict much more SO_3 than is actually present. At the operating temperatures of 280°F to 290°F, the value of resistivity predicted by Model II is two orders of magnitude low because the actual SO_3 concentration was only 10 percent of the value predicted. Nevertheless, by interpolating visually between the resistivity curves produced by Model II, it can be seen that a prediction of Model II for the actual SO_3 concentration would agree well with the in situ measurement.

The data from Plant 2 illustrate the possible pitfall in relying solely on a computer model prediction of the SO_3 concentration. The measured SO_3/SO_2 ratio at Plant 2 was much lower than the average ratio that is used in the computer models. The reason for the unusually low SO_3 concentration at this site was not determined, but such anomalies are usually attributed to interactions of sulfuric acid vapor with the ash and metal surfaces in the regenerative air heater. A detailed discussion of these issues is given in Reference 5.

Plant 2 provided the only opportunity in this test program to compare hopper ash samples with ash samples collected from the gas stream by the resistivity probes. The most striking differences in the ash analyses given in Table II are the differences in loss-on-ignition (LOI) values, which are unexplained. The small differences in mineral analyses cause negligible difference in the resistivity curves that are produced by the computer models. However, there is a substantial difference in the laboratory resistivity measurements, which were performed without any SO_3. The difference in resistivity of hopper ash samples and ash samples collected in situ probably results from differences in particle size distribution and particle packing density in the laboratory test cells. Larger particles are collected in the inlet field hopper of an ESP, with the smaller particles penetrating to the middle and outlet fields. This is not a uniform fractionation, however, as rapping reentrainment tends to redistribute the particles among the middle and outlet fields.

Figures 5 and 6 illustrate the two complete data sets collected on the first test day at Plant 3. Table III shows separate analyses of ash samples collected in situ by the SRI and SCS resistivity probes during the first and third tests. In both cases, the two different ash mineral analyses cause negligible difference in the resistivity curves that are produced by the computer models. Plant 3 had the highest coal sulfur of the three plants tested. This fact is reflected in the higher SO_3 concentrations measured and predicted. The SO_3 concentrations of 6 to 7 ppm predicted by the computer models compare well with the values of 7 to 8 ppm measured on the first test day. Since the measured SO_3/SO_2 ratio can vary widely about the average ratio that is used in the resistivity models, this level of agreement between measurement and prediction is considered to be good.

Independent and simultaneous measurements of in situ ash resistivity by SRI and SCS personnel are shown on both Figures 5 and 6. The data obtained during the afternoon of the first test day, Figure 6, show the effect of a 20°F difference in gas temperature between the two different sampling

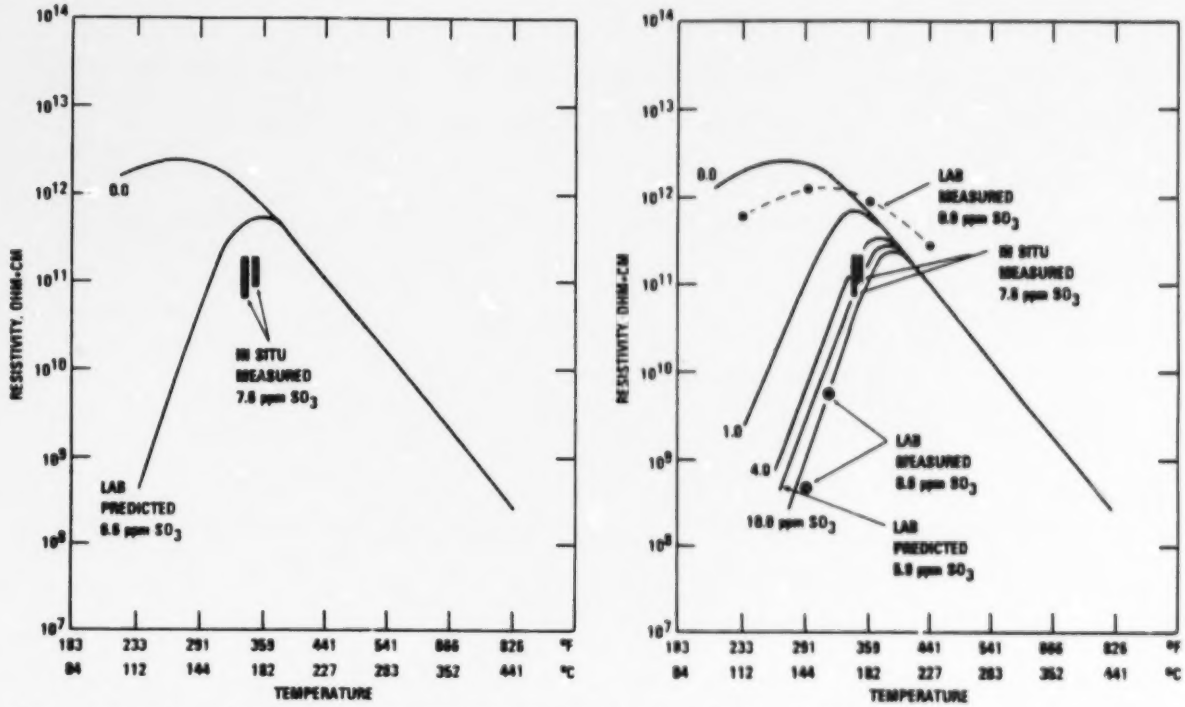

Figure 5. Plant 3 fly ash resistivity data, 8/28/85 AM, with Model I (left) and Model II (right) predicted resistivity curves.

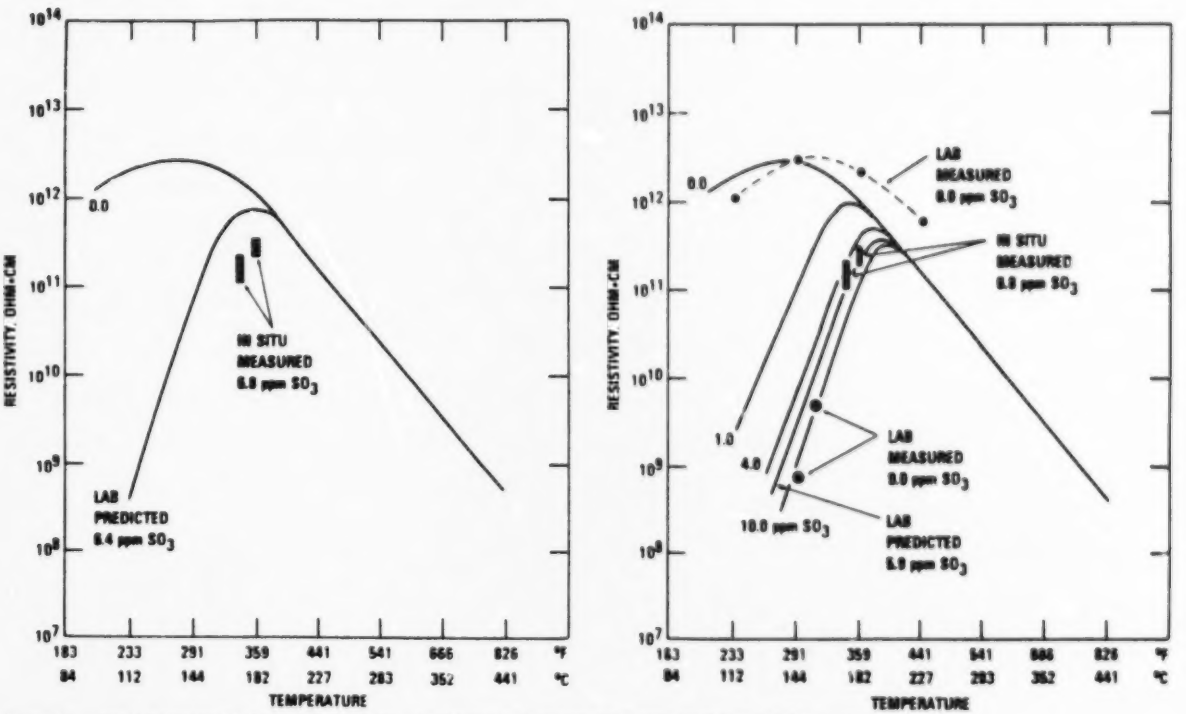

Figure 6. Plant 3 fly ash resistivity data, 8/28/85 PM with Model I (left) and Model II (right) predicted resistivity curves.

ports. In both figures it can be seen that the in situ ash resistivity measurements agree much better with Model II predictions than with Model I. Furthermore, the laboratory resistivity measurements performed with SO_3 at two lower temperatures agree well with Model II predicitions.

Summary

Good agreement is usually obtained between the three methods of determining fly ash resistivity values. However, the data from Plant 2 provide an example where the measured SO_3 concentration in the flue gas is very different from the predicted value. This example illustrates the possible pitfall in relying solely on a computer model prediction of SO_3 and its effect on fly ash resistivity. In any case, Model II of the Bickelhaupt resistivity predictor gives consistently better agreement than Model I with resistivity values measured both in situ and in the laboratory.

The in situ resistivity data were obtained with two different point-plane probes manufactured in two different shops and used by four different operators. Consistent data were obtained. In the present state of limited knowledge of relationships between coal characteristics and fly ash resistivity, it is advisable to measure the resistivity in situ with a point plane probe during a test burn of the coal.[2] If the resistivity is predicted from coal and ash analyses, Model II of the Bickelhaupt computer program should be used.[4] If the computer program is used to predict variations in resistivity with temperature inside an operating ESP, the SO_3 concentration in the flue gas should be measured by the Cheney-Homolya method of controlled condensations[2] and used as input data for the computer program instead of depending on the model to predict a value of SO_3. When troubleshooting an operating ESP which has electrical operating difficulties, a combination of all three methods of determining fly ash resistivity values is recommended in order to discern any unexpected anomalies in the fly ash properties.

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